Study of ω-, η-, η'- and D^--mesic nuclei

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Using the quark-meson coupling (QMC) model, we investigate whether ω, η, η' and D^- mesons form meson-nucleus bound states. Our results suggest that one should expect to find η- and ω-nucleus bound states in all the nuclei considered. Furthermore, it is shown that the D^- meson will form quite narrow bound states with ^{208}Pb.

To study the medium modification of the light vector (ρ, ω and ϕ) meson masses is very interesting because it is expected to provide us information concerning chiral symmetry (restoration) in a nuclear medium. Such experiments carried out by the CERES and HELIOS collaborations at the CERN/SPS [1], and those planned at TJNAF and GSI [2], are closely related to this issue. Recently, an alternative approach to study meson mass shifts in nuclei was suggested by Hayano *et al.* [3] to produce η and ω mesons with nearly zero recoil, which inspired the theoretical investigations of η- and ω-mesic nuclei [4,5]. The interesting point of the suggestion is that the meson is expected to be bound in a nucleus, if the meson feels a large enough attractive (Lorentz scalar) force inside the nucleus. We will report here the results for the mesic nuclei those studied using the quark-meson coupling (QMC) model [5,6]. (See Refs. [7–9] for the QMC model.)

Concerning charmed mesic nuclei [6], it is in some ways even more exciting, in that it promises more specific information on the relativistic mean fields in nuclei and the nature of dynamical chiral symmetry breaking. We focus on systems containing an anti-charm quark and a light quark, $\bar{c}q$ $(q = u, d)$, which have no strong decay channels if bound. If we assume that dynamical chiral symmetry breaking is the same for the light quark in the charmed meson as in purely light-quark systems, we expect the same coupling constant, g_σ^q, in QMC. In the absence of any strong interaction, the D^- will form atomic states, bound by the Coulomb potential. The resulting binding for, say, the 1s level in ^{208}Pb is between ten and thirty MeV and should provide a very clear experimental signature. On the other hand, although we expect the D-meson (systems of $\bar{q}c$) will form deeply bound D-nucleus states, they will also couple strongly to open channels such as $DN \to B_c(\pi's)$, with B_c a charmed baryon. Unfortunately, because our present knowledge does not permit an accurate calculation of the D-meson widths in a nucleus, results for the D-mesic nuclei may not give useful information for experimenters.

In Figs. 1 and 2 we show the mass shifts of the mesons in symmetric nuclear matter [5,6]. The masses for the physical ω, η and η' are calculated using the octet and singlet states with the mixing angles, $\theta_P = -10°$ for (η, η'), and $\theta_V = 39°$ for (ϕ, ω) [10]. The masses for the octet and singlet states without the mixing are also shown (the dotted lines).

At position $\vec{r}$ in a nucleus the Dirac equations for the quarks and antiquarks in the

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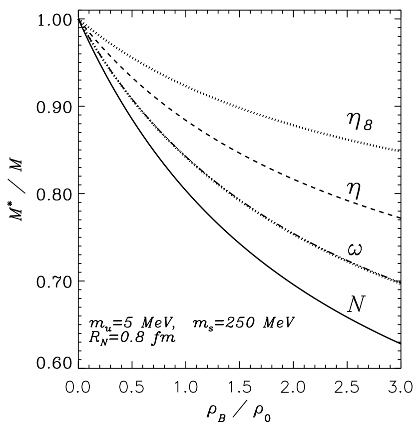

Figure 1. Effective masses in symmetric nuclear matter. ($\rho_0 = 0.15$ fm^{-3}.)

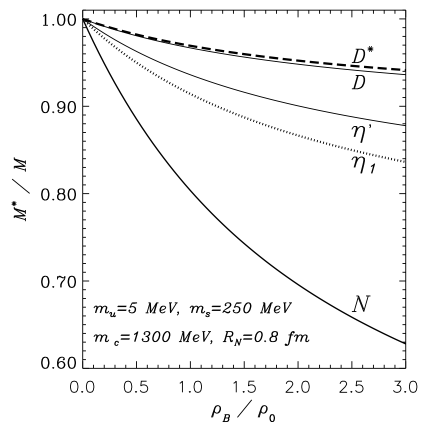

Figure 2. See the caption of Fig. 1.

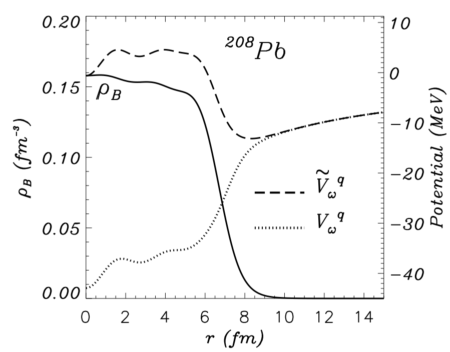

Figure 3. Total potential for the D^-.

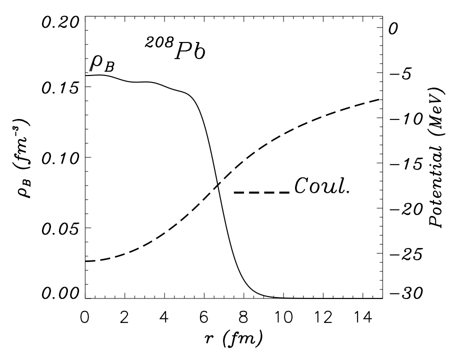

Figure 4. Coulomb potential for the D^-.

meson bags ($|\vec{x}-\vec{r}| \leq$ bag radius) are given by [5,6,11]:

$$\left[i\gamma\cdot\partial_x - (m_q - V^q_\sigma(\vec{r})) \mp \gamma^0\left(V^q_\omega(\vec{r}) + \frac{1}{2}V^q_\rho(\vec{r})\right)\right]\begin{pmatrix}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{pmatrix} = 0, \tag{1}$$

$$\left[i\gamma\cdot\partial_x - (m_q - V^q_\sigma(\vec{r})) \mp \gamma^0\left(V^q_\omega(\vec{r}) - \frac{1}{2}V^q_\rho(\vec{r})\right)\right]\begin{pmatrix}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{pmatrix} = 0, \tag{2}$$

$$[i\gamma\cdot\partial_x - m_{s,c}]\,\psi_{s,c}(x)\ (\text{or } \psi_{\bar{s},\bar{c}}(x)) = 0, \tag{3}$$

where the mean-field potentials for a bag centered at position $\vec{r}$ in the nucleus, are calculated self-consistently in QMC by solving Eqs. (23) – (30) of Ref. [8].

Then, the meson masses in the nucleus are calculated by [5,6]:

$$m^*_{\eta,\omega}(\vec{r}) = \frac{2[a^2_{P,V}\Omega^*_q(\vec{r}) + b^2_{P,V}\Omega_s(\vec{r})] - z_{\eta,\omega}}{R^*_{\eta,\omega}} + \frac{4}{3}\pi R^{*3}_{\eta,\omega}B, \qquad (\text{for } \eta',\ a_P \leftrightarrow b_P), \tag{4}$$

$$m^*_D(\vec{r}) = \frac{\Omega^*_q(\vec{r}) + \Omega_c(\vec{r}) - z_D}{R^*_D} + \frac{4}{3}\pi R^{*3}_D B, \tag{5}$$

$$\left.\frac{\partial m^*_j(\vec{r})}{\partial R_j}\right|_{R_j=R^*_j} = 0, \qquad (j = \omega, \eta, \eta', D), \tag{6}$$

$$a_{P,V} \equiv \sqrt{1/3}\cos\theta_{P,V} - \sqrt{2/3}\sin\theta_{P,V}, \quad b_{P,V} \equiv \sqrt{2/3}\cos\theta_{P,V} + \sqrt{1/3}\sin\theta_{P,V}, \tag{7}$$

where $\Omega_q^*(\vec{r}) = \sqrt{x_q^2 + (R_j^* m_q^*)^2}$, with $m_q^* = m_q - g_\sigma^q \sigma(\vec{r})$ and $\Omega_{s,c}(\vec{r}) = \sqrt{x_{s,c}^2 + (R_j^* m_{s,c})^2}$.

In this study we chose the values, $(m_q, m_s, m_c) = (5, 250, 1300)$ MeV for the current quark masses, and $R_N = 0.8$ fm for the bag radius of the nucleon in free space. (See Ref. [8] for the other parameters.) We stress that exactly the same coupling constants in QMC, g_σ^q, g_ω^q and g_ρ^q, are used for the light quarks in the mesons as in the nucleon. However, in studies of the kaon system, we found that it was phenomenologically necessary to increase the strength of the vector coupling, g_ω^q, in the K^+ ($g_\omega^q \to 1.4^2 g_\omega^q$, i.e., $V_\omega^q(r) \to \tilde{V}_\omega^q(r) = 1.4^2 V_\omega^q(r)$) in order to reproduce the empirically extracted K^+-nucleus interaction [11]. This may be ascribed to the fact that the kaon is a pseudo-Goldstone boson and expected to be difficult to treat properly with the usual bag model. Thus, we show results for the $\bar{D}$ bound state energies with both choices for the vector potential, $V_\omega^q(r)$ and $\tilde{V}_\omega^q(r)$.

In Fig. 3 we show the calculated potentials for the D^-. The left panel shows the *naive* sum of the potentials, $(m_{D^-}^*(r) - m_{D^-}) + [V_\omega^q(r)$ or $\tilde{V}_\omega^q(r)] + \frac{1}{2}V_\rho^q(r) - A(r)$ (the dotted or dashed line). The right panel shows the Coulomb potential. One expects the existence of the ${}^{208}_{D^-}$Pb states just from inspection of the sum of the potentials, because the D^- is heavy and may be described well in the nonrelativistic Schrödinger equation.

Table 1
η, ω and η' bound state energies (in MeV), $E_j = Re(E_j^* - m_j)$ $(j = \eta, \omega, \eta')$, where all widths for the η' are set to zero. The eigenenergies are given by, $E_j^* = E_j + m_j - i\Gamma_j/2$.

		$\gamma_\eta = 0.5$		γ_ω=0.2		$\gamma_{\eta'} = 0$
		E_η	Γ_η	E_ω	Γ_ω	$E_{\eta'}$
${}^{6}_{j}$He	1s	-10.7	14.5	-55.6	24.7	* (not calculated)
${}^{11}_{j}$B	1s	-24.5	22.8	-80.8	28.8	*
${}^{26}_{j}$Mg	1s	-38.8	28.5	-99.7	31.1	*
	1p	-17.8	23.1	-78.5	29.4	*
	2s	—	—	-42.8	24.8	*
${}^{16}_{j}$O	1s	-32.6	26.7	-93.4	30.6	-41.3
	1p	-7.72	18.3	-64.7	27.8	-22.8
${}^{40}_{j}$Ca	1s	-46.0	31.7	-111	33.1	-51.8
	1p	-26.8	26.8	-90.8	31.0	-38.5
	2s	-4.61	17.7	-65.5	28.9	-21.9
${}^{90}_{j}$Zr	1s	-52.9	33.2	-117	33.4	-56.0
	1p	-40.0	30.5	-105	32.3	-47.7
	2s	-21.7	26.1	-86.4	30.7	-35.4
${}^{208}_{j}$Pb	1s	-56.3	33.2	-118	33.1	-57.5
	1p	-48.3	31.8	-111	32.5	-52.6
	2s	-35.9	29.6	-100	31.7	-44.9

To calculate the bound state energies for the mesons with the situation of almost zero momenta, we may solve the following form of the Klein-Gordon equation [5,6]:

$$[\nabla^2 \;+\; (E_j^* - V_v^j(r))^2 - \tilde{m}_j^{*2}(r)]\,\phi_j(\vec{r}) = 0, \qquad (j = \omega, \eta, \eta', D), \tag{8}$$

$$\tilde{m}_j^*(r) \;\equiv\; m_j^*(r) - \frac{i}{2}\left[(m_j - m_j^*(r))\gamma_j + \Gamma_j^0\right] \;\equiv\; m_j^*(r) - \frac{i}{2}\Gamma_j^*(r), \tag{9}$$

Table 2
D^-, $\bar{D}^0$ and D^0 bound state energies (in MeV). The widths are all set to zero.

state	$D^-(\tilde{V}^q_\omega)$	$D^-(V^q_\omega)$	$D^-(V^q_\omega$, no Coulomb)	$\bar{D}^0(\tilde{V}^q_\omega)$	$\bar{D}^0(V^q_\omega)$	$D^0(V^q_\omega)$
1s	-10.6	-35.2	-11.2	unbound	-25.4	-96.2
1p	-10.2	-32.1	-10.0	unbound	-23.1	-93.0
2s	-7.7	-30.0	-6.6	unbound	-19.7	-88.5

where E^*_j is the total energy of the meson, $V^j_v(r)$, m_j and Γ^0_j are the sum of the vector and Coulomb potentials, the corresponding masses and widths in free space, and γ_j are treated as phenomenological parameters to describe the in-medium meson widths, $\Gamma^*_j(r)$ [5,6]. We show the bound state energies calculated for $\gamma_\eta = 0.5$ and $\gamma_\omega = 0.2$, which are expected to correspond best with experiment according to the estimates in Refs. [3,12]. For the D^- and $\bar{D}^0$, the widths are set to zero which is exact, whereas those for the η' and D^0 do not make sense. The calculated bound state energies are listed in Tables 1 and 2.

Our results suggest that η and ω mesons should be bound in all the nuclei considered. Furthermore, the D^- meson should be bound in ^{208}Pb, due to two different mechanisms, namely, the scalar and attractive σ mean field for the case of $V^q_\omega(r)$ even without the Coulomb force, or solely due to the Coulomb force for the case of $\tilde{V}^q_\omega(r) = 1.4^2 V^q_\omega(r)$. The existence of any bound states at all would give us important information concerning the role of the Lorentz scalar σ field, and hence dynamical symmetry breaking.

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